

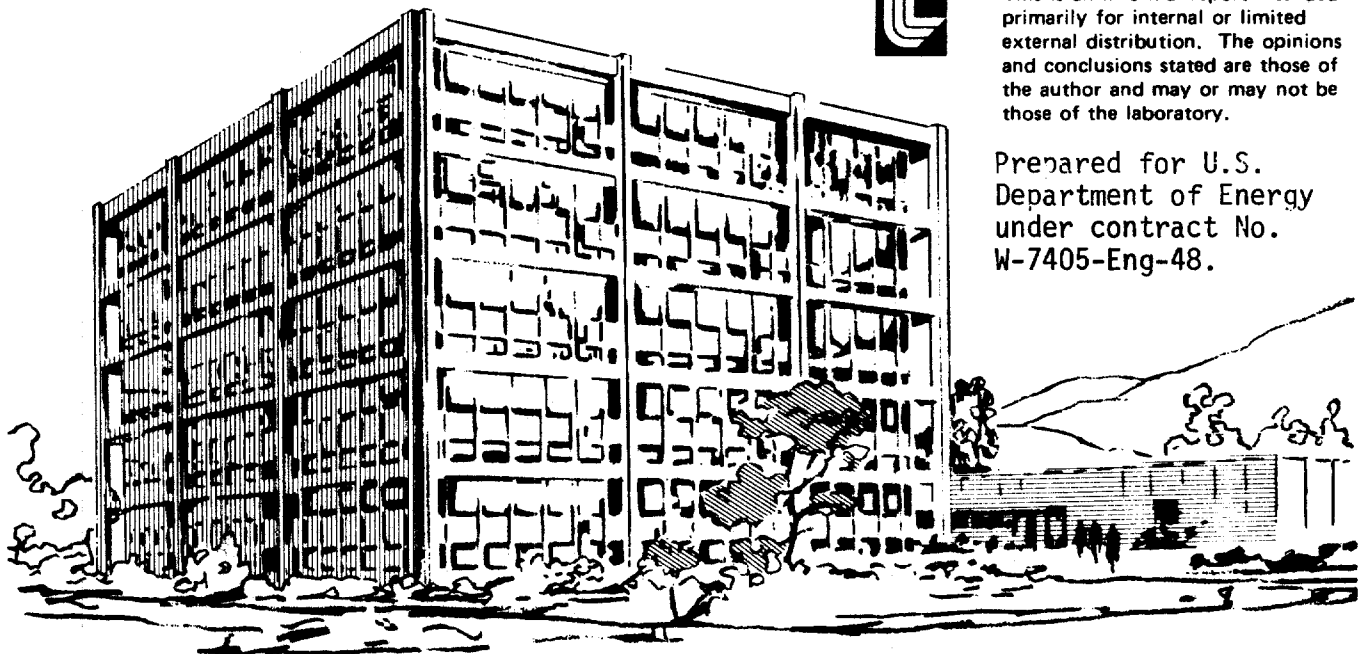
# **Lawrence Livermore Laboratory**

THE SPREADING AND DIFFERENTIAL BOIL-OFF FOR A SPILL  
OF LIQUID NATURAL GAS ON A WATER SURFACE

WERNER STEIN

December 1978

**CIRCULATION COPY**  
**SUBJECT TO RECALL**  
**IN TWO WEEKS**



This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the laboratory.

Prepared for U.S.  
Department of Energy  
under contract No.  
W-7405-Eng-48.

## DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

This report has been reproduced  
directly from the best available copy.

Available to DOE and DOE contractors from the  
Office of Scientific and Technical Information  
P.O. Box 62, Oak Ridge, TN 37831  
Prices available from (615) 576-8401, FTS 626-8401

Available to the public from the  
National Technical Information Service  
U.S. Department of Commerce  
5285 Port Royal Rd.,  
Springfield, VA 22161

LAWRENCE LIVERMORE LABORATORY  
UNIVERSITY OF CALIFORNIA  
LIVERMORE, CALIFORNIA 94550

THE SPREADING AND DIFFERENTIAL BOIL-OFF FOR A SPILL\*  
OF LIQUID NATURAL GAS ON A WATER SURFACE

Werner Stein

Thermo Fluid Mechanics Group  
Nuclear Test Engineering Division

December 1978

ABSTRACT

A model for the unconfined spreading and evaporation of liquid natural gas (LNG) when spilled on a water surface has been developed. The model includes a model for differential boil-off of the LNG constituents. A listing of the computer code, LNGVG, developed for making these calculations is included. This code can be used to calculate effects for instantaneous, continuous or finite duration continuous spills. Calculations for two spill experiments conducted at China Lake have been made and are compared to the experimental data.

\*"Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract number W-7405-ENG-48."

## INTRODUCTION

Liquid natural gas (LNG) is a cryogen with a boiling temperature, at 1 atm., of approximately 111° K. Spillage of LNG on a water surface results in a very rapid spreading into a circular shaped pool. During this spreading process, heat transfer from the relatively warm water to the cold LNG results in boiling of the LNG with a resultant high rate of gas vapor generation.

LNG is composed primarily of methane with small fractions of ethane and propane. These constituents have different heats of vaporization and boiling points with the result that they boil off at different rates. This differential boil-off during vapor generation results in LNG vapors containing different fractions of constituents than the originally spilled LNG.

A computer program called LNGVG to calculate LNG Vapor Generation and differential boil off has been written. Using this code, calculations of pool radius, differential boil-off, spreading rate and pool break-up can be made for instantaneous, continuous, and finite duration continuous spills of LNG on water. Using this code, two calculations have been made to predict the boil off of each constituent of LNG for two spill tests conducted at China Lake.<sup>[1]</sup> A listing of this code is given in Appendix A.

## DISCUSSION

The calculations for the spreading of LNG are approached by determining the velocity of the leading edge of the LNG pool. This velocity is determined by considering the outer edge as a density intrusion. The radius of the pool as a function of time is determined from the velocity equation.

Pool break-up is assumed to occur after spilling has stopped and when the thickness of the LNG reaches an experimentally determined minimum thickness,

due to spreading and evaporation. The break-up is observed to occur at the center of the pool first and spreads radially outward until all the LNG has evaporated. [2]

The rate of evaporation of LNG from a water surface is often determined experimentally and given as a regression rate (i.e., cm./min.). This regression rate represents the sum of the contributions from each of the LNG constituents. The fraction of this regression rate applicable to each of the constituents is determined in the calculations by the relative magnitudes of their heats of vaporization, boiling temperature and volume fraction. This relative fraction of total boil-off for each constituent varies with time and is different from the original volume fraction of the LNG.

#### LNG SPILL SCENARIO

The phenomena that occur during a continuous spill of finite duration are described below. The LNG is assumed to be spilled at a constant rate for a finite time.

- (1) Initially the LNG spreads radially at a rapid rate, which decreases as the radius increases. Boil-off of the LNG takes place as soon as the LNG contacts the water surface. Due to the differential boil-off phenomenon, the vapors generated have different volume fractions than the initial LNG. Also, the volume fraction of the LNG constituents of the LNG on the water surface changes due to the differential boil-off.
- (2) The LNG spreads out to a radius large enough to vaporize an amount of LNG equal to the rate of LNG spill. The composition of the LNG spilled on the water surface continues to change due to differential boil-off until a condition is reached where the rate of

boil-off of each LNG constituent equals the rate of spillage of each constituent.

- (3) Steady conditions are maintained until the spillage is stopped. Once spilling has stopped, the volume fraction of each constituent in the spilled LNG changes due to differential boil-off and the vapors generated again have volume fractions different from the original LNG volume fractions.
- (4) The volume of LNG left on the water decreases as vapor generation takes place until the pool begins to break up in the center. Initially just a small circular area of water is visible. This circular area increases with time until the entire mass of LNG has evaporated.

#### ANALYTICAL RELATIONS

The radius of the LNG spilled on the water surface is given by equation(1):<sup>[3]</sup>

$$(1) \quad r = 1.35 \left( g \frac{\rho_w - \rho_{LNG}}{\rho_w} \right)^{1/4} V^{1/4} t^{1/2}$$

where:  $r$  = radius

$\rho$  = density of LNG or water (w)

$V$  = volume of LNG on water surface

$t$  = time

The velocity of the leading edge of the LNG is given by differentiating equation (2) with respect to time while holding  $V$  constant:

$$(2) \quad \left( \frac{dr}{dt} \right)_{V=\text{constant}} = \frac{1.35}{2} \left[ g \frac{\rho_w - \rho_{LNG}}{\rho_w} \right]^{1/4} V^{1/4} t^{-1/2}$$

The method of applying the above equations is to calculate the spreading for very short time increments using a constant LNG volume during the time increment. After each time increment, the volume remaining is adjusted to account for LNG added during spilling and loss due to evaporation. Thus, the radius after N+1 successive time intervals,  $\Delta t$ , is given by:

$$(3) \quad r_{N+1} = r_N + \left( \frac{dr}{dt} \right)_{V=V_N} \Delta t$$

and the volume  $V_N$  is given by: [3]

$$(4) \quad V_N = V_{N-1} + [\dot{V} - EV_{N-1}] \Delta t$$

where:  $\dot{V}$  = rate of addition of LNG

$EV$  = Rate of evaporation of LNG

In the case of a continuous LNG spill, the maximum radius of the pool is given by:

$$(5) \quad \dot{V} = \pi R^2 K$$

where:  $R$  = maximum pool radius

$K$  = LNG regression rate (length/time)

After spillage of the LNG has stopped, the maximum radius,  $R$ , attained by the pool is assumed to remain constant. During this condition, evaporation takes place until the average LNG pool thickness,  $h$ , equals 0.183 cm. [2] and thereafter pool break-up occurs. Pool break-up initially occurs at the center

of the pool and spreads radially outward as LNG is evaporated. During pool break-up, the LNG thickness is assumed to remain constant at 0.183 cm. This value has been experimentally obtained with other researchers<sup>[4]</sup> obtaining different values, up to a factor of 3 larger. Using larger values for pool break-up results in pool break-up occurring sooner.

Also experimentally obtained is the rate of LNG boil-off expressed as a regression rate in units of, for example, cm. of LNG per second. A value of 0.0423 cm. per second<sup>[5]</sup> was used in the subsequent China Lake calculation. This rate represents the sum of the regression rates for each of the various constituents of the LNG. The regression rate for any individual constituent, I, is calculated as follows with I = 1 corresponding to methane (CH<sub>4</sub>):

$$(6) \quad K = \sum_I \frac{(C_p \Delta T + HVAP)_{CH_4} \rho_{CH_4} FRI(I) A}{(C_p \Delta T + HVAP)_I \rho_I} = \sum_I K_I FRI(I)$$

where  $K$  = experimentally determined LNG regression rate

$C_p$  = specific heat

$\Delta T$  = number of degrees that the boiling temperature of constituent I is above the initial LNG boiling temperature.

HVAP = heat of vaporization

$\rho_I$  = liquid density of constituent I

FRI(I) = volume fraction of constituent I in the original LNG

A = unknown regression rate to be solved for.

Solving (6) for "A" and plugging into the below equation (7) gives the regression rate,  $K_I$ , of constituent I:

$$(7) \quad K_I = \frac{(C_p \Delta T + HVAP)_{CH_4} \rho_{CH_4} A}{(C_p \Delta T + HVAP)_I \rho_I}$$

The LNG spilled initially on the water contains various volume fractions of constituents. Throughout the calculations a mass balance is calculated for each constituent in the spilled LNG. Addition of constituents to the spilled LNG is determined from the rate of spill and the known volume fractions of the LNG. Loss of constituents from the spilled LNG is by evaporation. The amount evaporated in a time step  $\Delta t$  of constituent I is given by  $\Delta V_I$ :

$$\Delta V_I = K_I F S \Delta t$$

where:  $F$  = volume fraction of constituent I in the LNG pool

$S$  = surface area covered by LNG pool

In the calculations, the mixture of the constituents is always assumed to be homogeneous.

#### CALCULATIONS

The above relations have been incorporated into a computer code called LNGVG. A listing is provided in Appendix A. Use of this code involves generating an input file called LNGIN which contains the information called for by the read statements 6 and 8. Input variables and their units are described in the comment cards at the beginning of the code. Output is all contained in an output file called LNGOUT.

Calculations for two anticipated spills at China Lake have been made. The initial conditions for each spill are given below:

Spill Number	:	<u>LNG 18</u>	<u>LNG 19</u>
Volume of LNG spilled ( $m^3$ )	=	4.4	4.0
Rate of LNG spillage ( $m^3/min$ )	=	4.0	4.0

Volume fraction of constituents in the LNG: Methane (CH <sub>4</sub> )	=	0.9423	0.9504
Ethane	=	0.0436	0.0391
Propane	=	0.0110	0.0075
LNG Boiling Temperature	=	111.7° K (201° R)	111.7° K (201° R)
LNG Regression Rate (cm/sec)	=	0.0423	0.0423
Water Density (kg/m <sup>3</sup> )	=	1,000	1,000
Initial LNG Density (kg/m <sup>3</sup> )	=	439	439
Wind Speed (m/sec)	=	10	2

## RESULTS

The results of the calculations for the volume fraction of each constituent in the vapors generated vs. time is shown in Figures 2 to 4 for test LNG 18 and in Figures 5 to 7 for test LNG 19. From these figures, one sees that the initial volume fraction of methane in the vapors is greater than the original fractions in the LNG, and the initial volume fractions of ethane and propane are less than the original LNG. The volume fractions in the vapor adjust themselves with time, however, until at the end of spilling, the vapors have approximately the same volume fraction as the original LNG. After spilling stops, the volume fraction of methane decreases and that of ethane and propane increases continuously until all the LNG has evaporated.

The maximum radius attained by the LNG pool in each test is 23 feet at a time of 23 seconds. Pool break-up is calculated to occur after 77 and 69 seconds for tests LNG 18 and 19 respectively.

The total boil-off rate (m<sup>3</sup>/sec) vs. time for each spill is shown on Figure 1.

## MODEL VERIFICATION

The above calculational results have been compared to experimental differential boil-off data. The data is shown in Figures 2 to 7. The data was obtained in each test from a measurement station, with station 1 and 2 located 25 and 50 feet respectively from the spill center. The data compares favorably with the calculations. The calculated curves appear to be slightly to the left of the experimental data points. This is possibly due to the fact that the LNG spilling from the spill pipe does not stop abruptly upon valve closing, but rather continues to spill out at a decreasing rate until the spill pipe is emptied. The calculations assumed a step change in starting and stopping the LNG spilling. If this is taken in account in the model, then the data points and calculated curves are expected to essentially coincide at times after spilling stops.

Also due to weathering of the LNG in the spill tanks, it is suspected that the LNG is not homogeneous but during initial spilling is weathered to some degree. In the spill tests only one sample of the LNG was taken, however, in future experiments numerous samples will be taken.

Comparisons with other models<sup>[5,6]</sup> have been made for instantaneous spills of LNG on water and the results are tabulated in Table I. The comparison involves maximum time to evaporate and maximum pool radius for instantaneous spills of 10 m<sup>3</sup> and 1000 m<sup>3</sup>. The calculated results from all three models agree rather well.

LNG 18 & LNG 19, CHINA LAKE TESTS

TOTAL VAPOR BOIL-OFF RATE

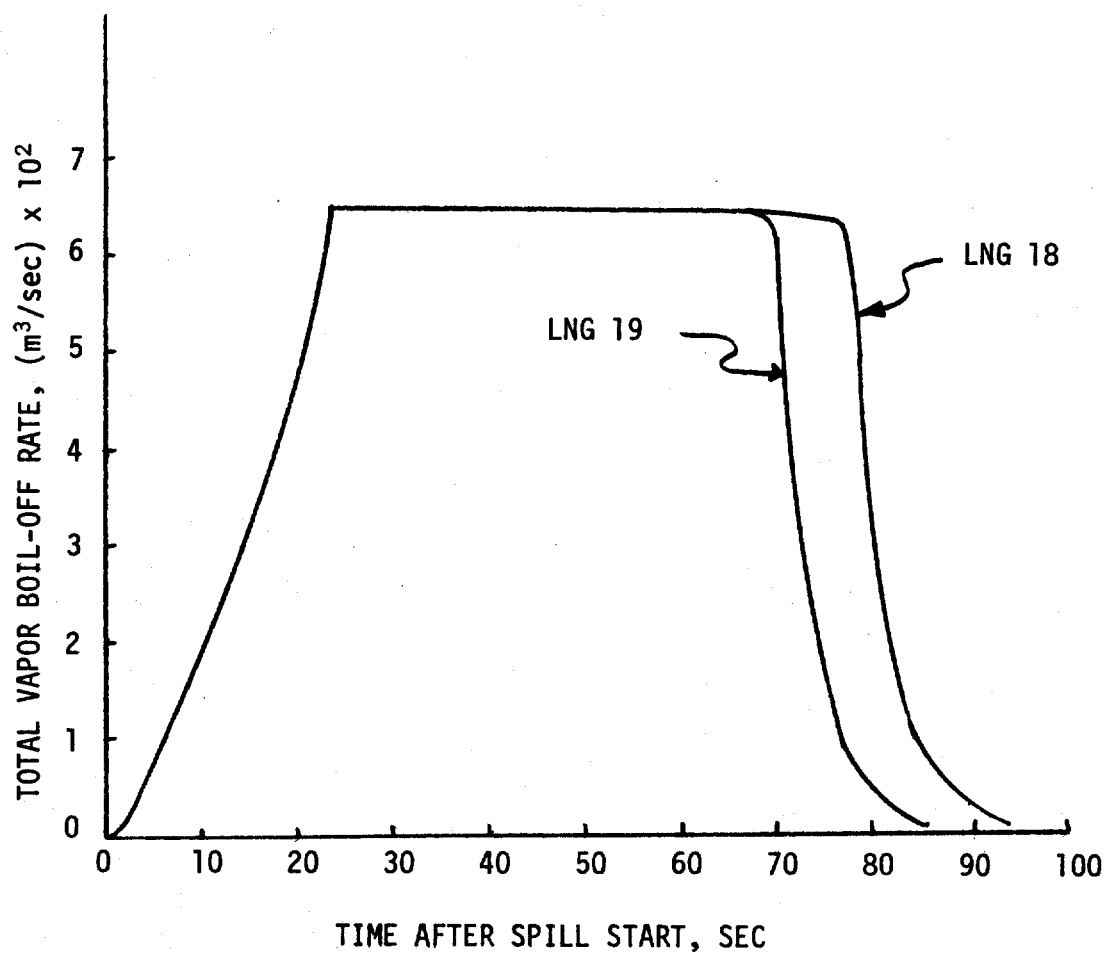


FIGURE 1

LNG 18, CHINA LAKE TEST

COMPARISON OF EXPERIMENTAL VS. CALCULATED  
METHANE VOLUME FRACTIONS IN LNG VAPOR

- △ - STATION #1 DATA  
○ - STATION #2 DATA

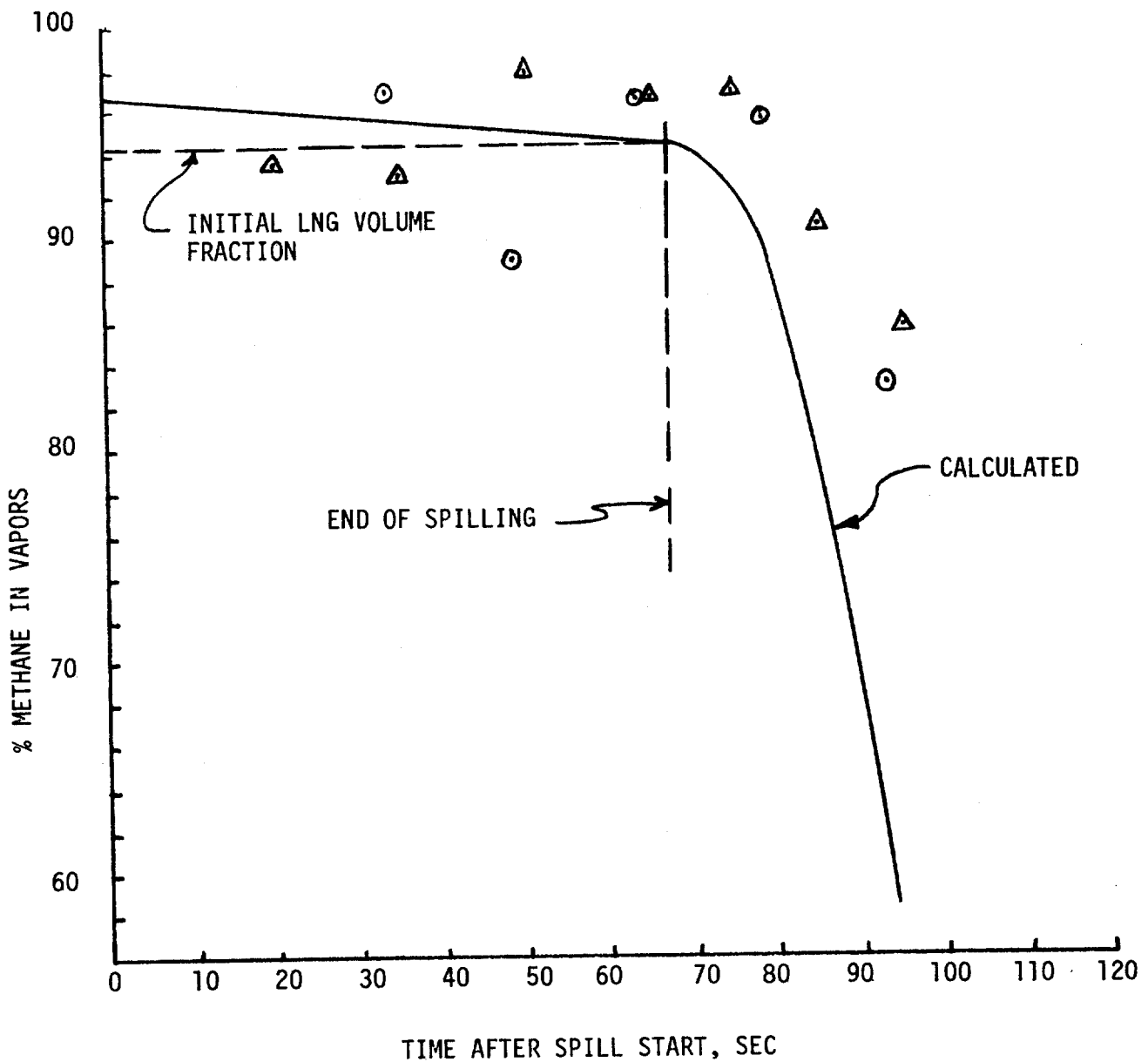


FIGURE 2

LNG 18, CHINA LAKE TEST

COMPARISON OF EXPERIMENTAL VS. CALCULATED  
ETHANE VOLUME FRACTIONS IN LNG VAPOR

△ - STATION #1 DATA

⊙ - STATION #2 DATA

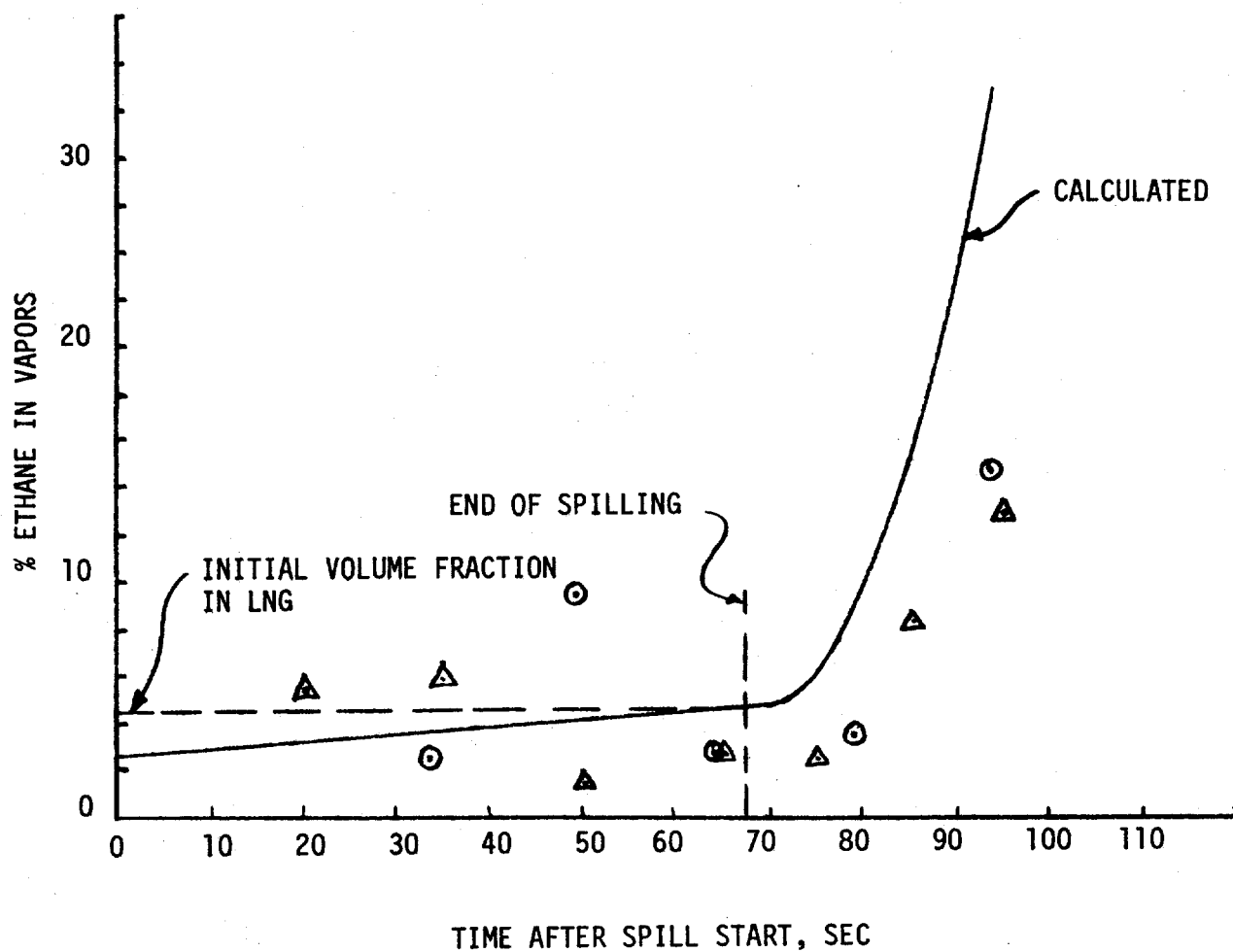


FIGURE 3

LNG 18, CHINA LAKE TEST

COMPARISON OF EXPERIMENTAL VS. CALCULATED  
PROPANE VOLUME FRACTIONS IN LNG VAPOR

△ - STATION #1 DATA

⊙ - STATION #2 DATA

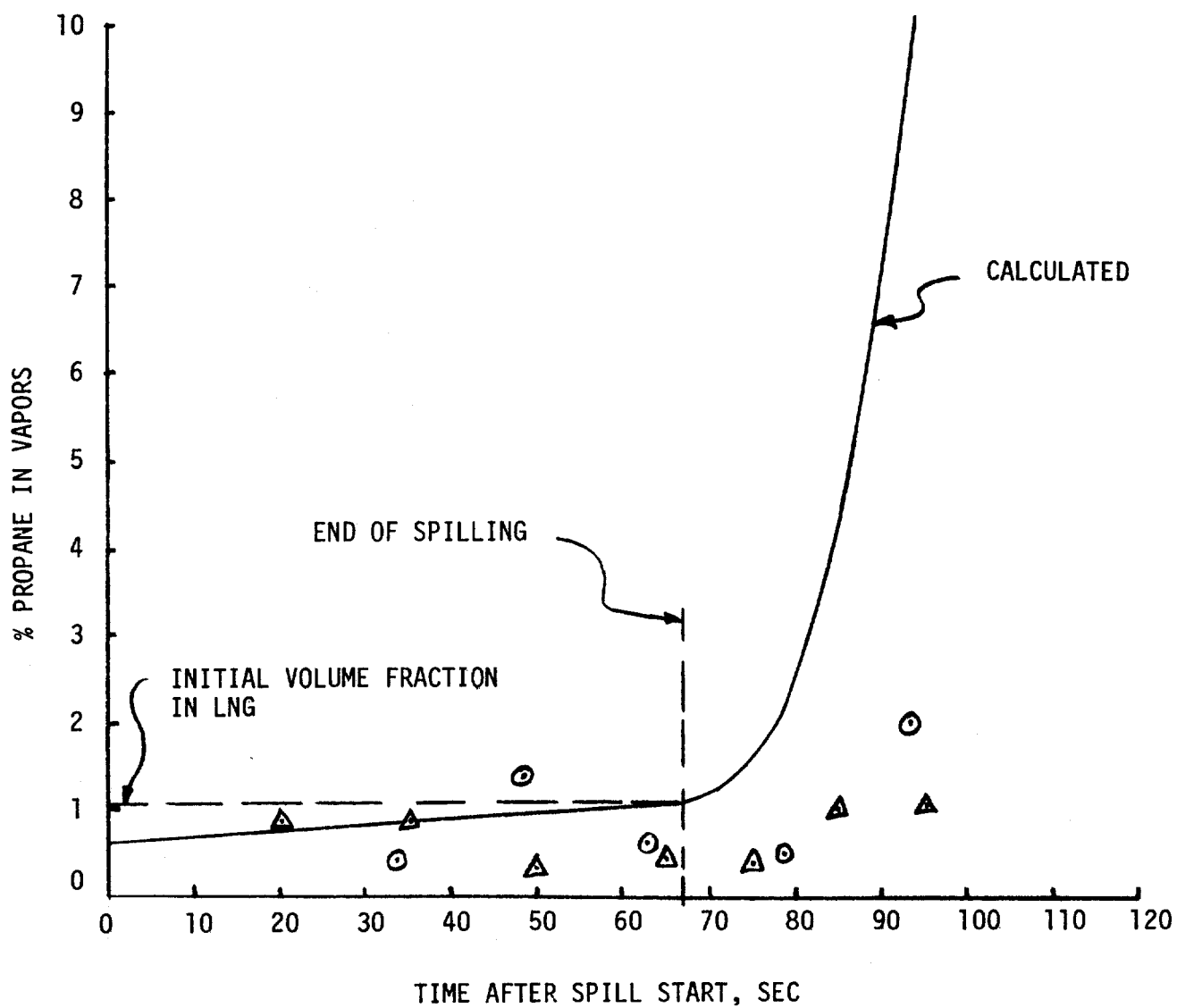


FIGURE 4

LNG 19, CHINA LAKE TEST

COMPARISON OF EXPERIMENTAL & CALCULATED  
METHANE VOLUME FRACTIONS IN LNG VAPOR

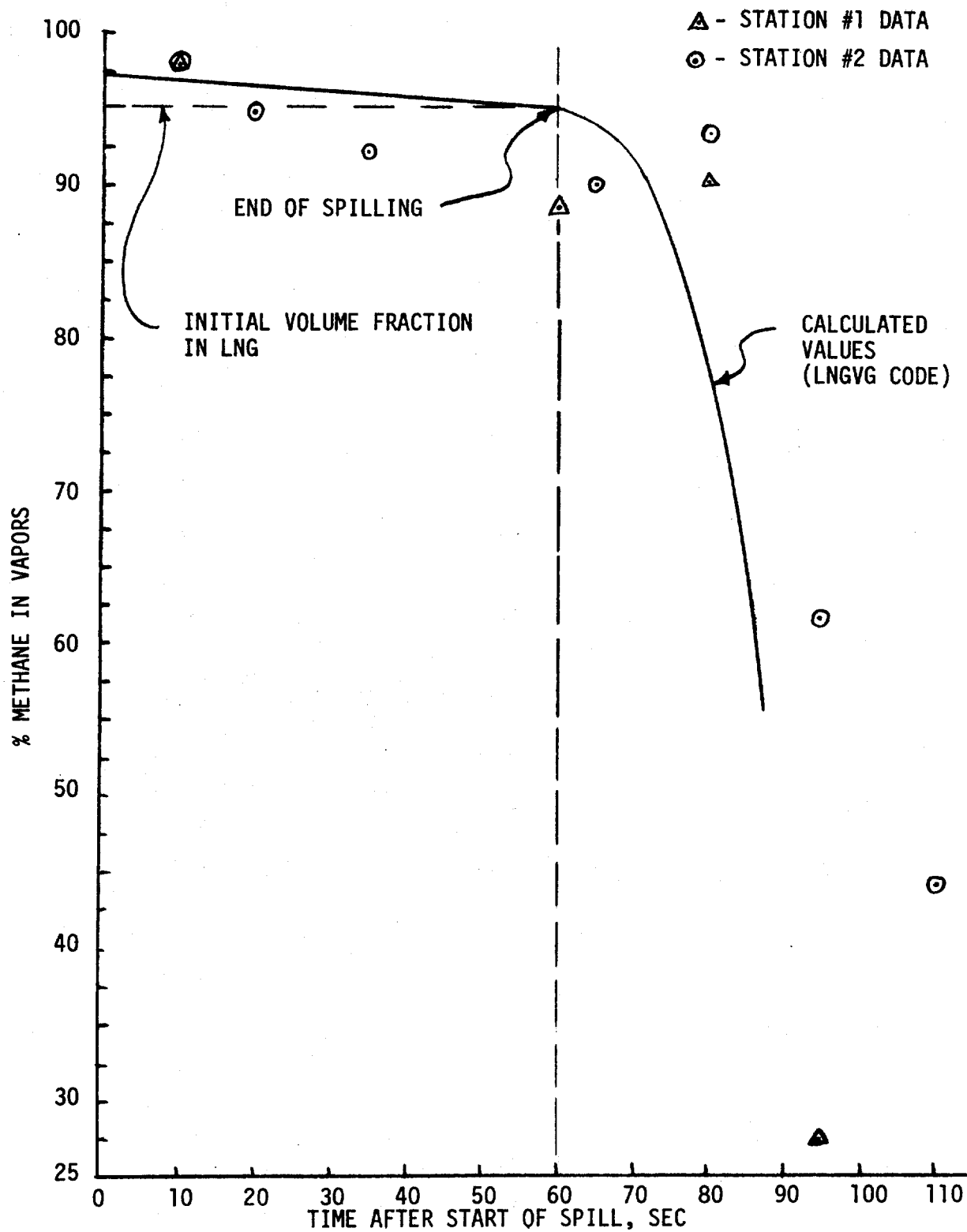


FIGURE 5

LNG 19, CHINA LAKE TEST  
COMPARISON OF EXPERIMENTAL VS. CALCULATED  
ETHANE VOLUME FRACTIONS IN LNG VAPOR

△ - STATION #1 DATA  
⊙ - STATION #2 DATA

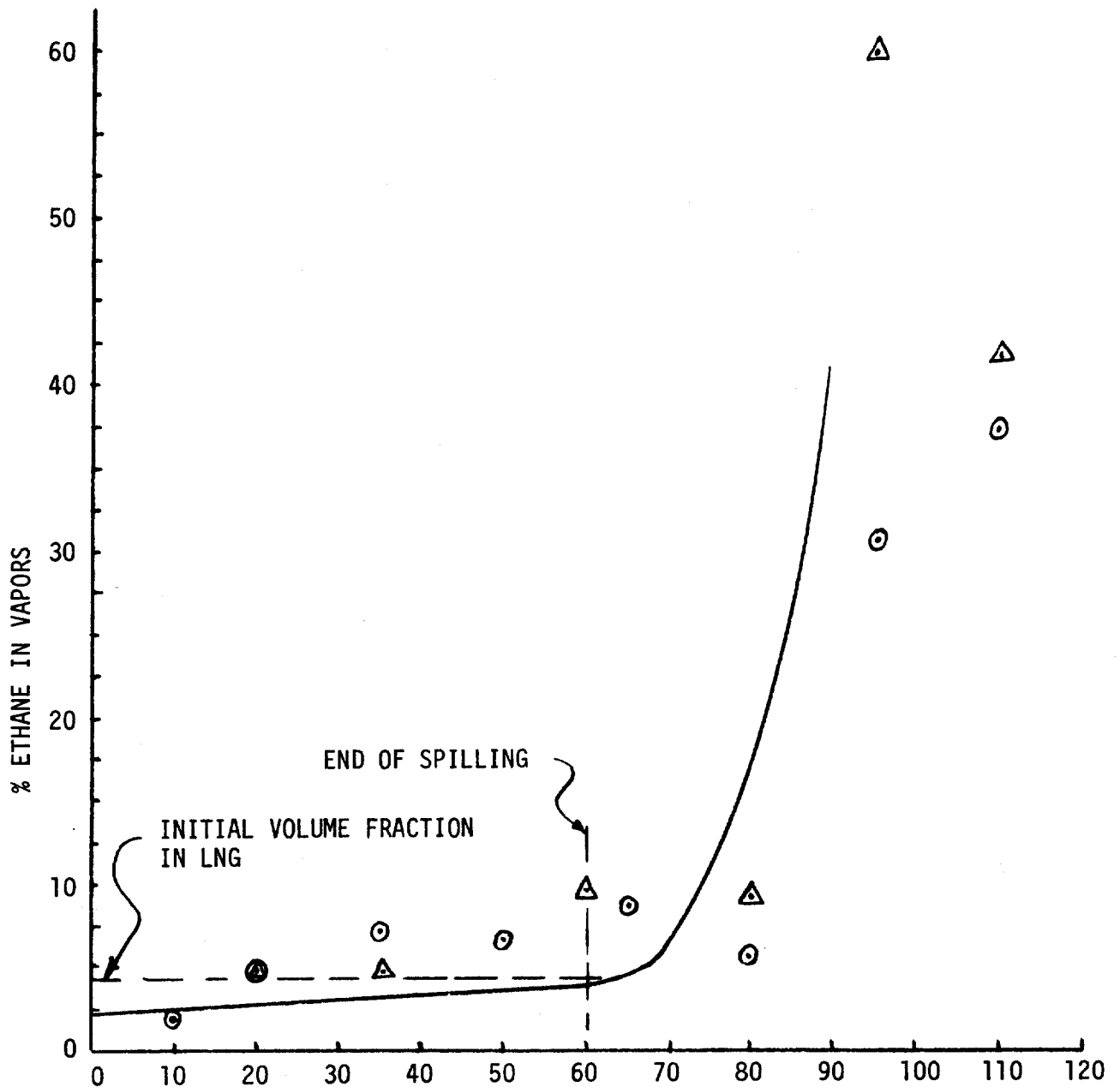


FIGURE 6

LNG 19, CHINA LAKE TEST

COMPARISON OF EXPERIMENTAL VS.  
CALCULATED PROPANE VOLUME FRACTIONS

△ - STATION #1 DATA

⊙ - STATION #2 DATA

△ @ 42.1%

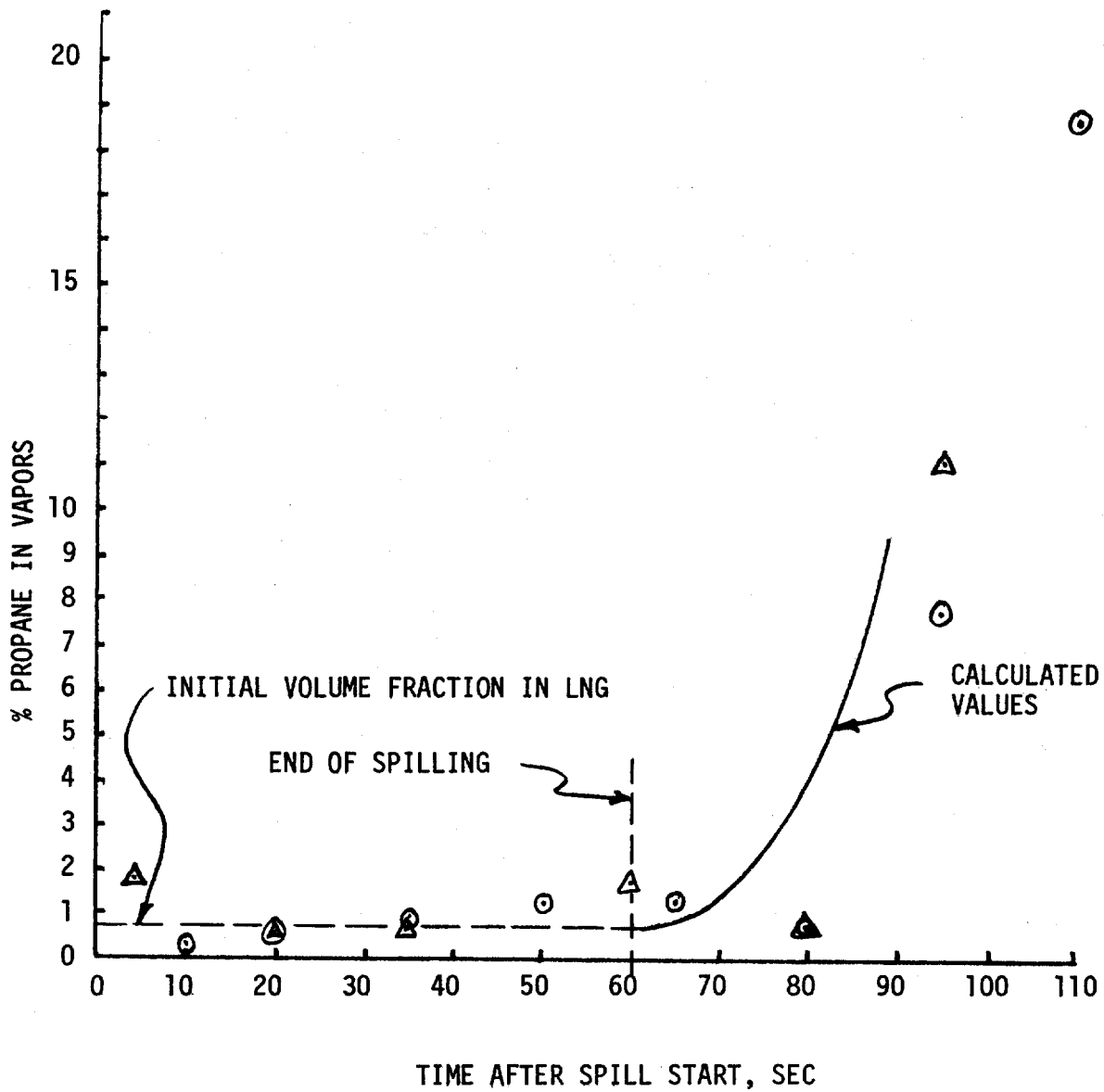


FIGURE 7

TABLE I

COMPARISON OF MAXIMUM POOL RADIUS, RMAX, AND TIME TO COMPLETE  
VAPORIZATION, TMAX, AS PREDICTED BY DIFFERENT ANALYSES

INSTANTANEOUS LNG SPILL VOLUME-LIQUID

ANALYSIS	10 M <sup>3</sup>		1000 M <sup>3</sup>	
	RMAX(M)	TMAX(SEC)	RMAX(M)	TMAX(SEC)
LNGVG	20	44	113	111
FAY <sup>[5]</sup>	16	24	109	108
RAJ <sup>[4]</sup>	20	38	115	120

REFERENCES

1. Private communication, W. Stein/R. Koopman, 13 November 1978.
2. Boyle, G. J., and Kneebone, A., "Laboratory Investigations into the Characteristics of LNG Spills on Water: Evaporation, Spreading, and Vapor Dispersion", Shell Research, Ltd., Report to A.P.I. Project on LNG Spills on Water, Ref. 6Z32, March 1973.
3. W. G. May and P. V. K. Perumal, "The Spreading and Evaporation of LNG on Water", ASME Annual Winter Meeting, Nov. 17-22, 1974, N.Y., N.Y.
4. G. E. Feldhauer, et al., "Spills of LNG on Water-Vaporization and Downwind Drift of Combustible Mixtures", Esso Research and Eng., Co., Report No. EEGIE-72, Pg. 52; 24 May 1972.
5. P. K. Raj and A. S. Kalelkar, "Fire Hazard Presented by a Spreading, Burning Pool of Liquified Natural Gas on Water", Paper No. 73-25, Page 8, Western States Section/The Combustion Institute 1973 Fall Meeting.
6. J. A. Fay, "Unusual Fire Hazard of LNG Tanker Spills", Combustion Science and Technology, 1973, Vol. 7, pp. 47-49.

# APPENDIX A

```

PROGRAM LNGVG(LNGIN,TAPE2=LNGIN,LNGOUT,TAPE3=LNGOUT)
CALL DEVICE(6HCREATE,6HLNGOUT,50000)
C A = REGRESSION RATE OF CONSTITUENT 1 OF THE LNG, FT/SEC
C AB = USED IN CALCULATING A
C CON = CONSTANT (0.675)
C CP(1) = SPECIFIC HEAT OF CONSTITUENT 1, BTU/LBM/F
C DELRO = DENSITY DIFF. BETWEEN WATER AND LNG ON WATER, LBM/CU.FT.
C DELV(1) = VOLUME OF CONSTITUENT 1 VAPORIZED DURING A TIME STEP, CU.FT
C DENS = SUMMATION OF DENSITY*VOLUME OF EACH LNG CONSTITUENT
C DENS1 = AVERAGE DENSITY OF LNG ON WATER
C DLVS(1) = VOLUME OF CONSTITUENT 1 VAPORIZED PER SEC., CU.FT./SEC
C FR(1) = VOLUME FRACTION OF CONSTITUENT 1 IN LNG VAPORIZED
C FRI(1) = VOLUME FRACTION OF CONSTITUENT 1 IN LNG SUPPLIED
C FRII(1) = VOLUME FRACTION OF CONSTITUENT 1 IN REMAINING SPILLED LNG
C G=ACCELERATION OF GRAVITY - FT/SEC/SEC
C H = AVERAGE HEIGHT OF LNG ON WATER SURFACE
C HBRK = THICKNESS OF LNG AT START OF POOL BREAKUP, FT.
C HVAP(1) = HEAT OF VAPORIZATION OF CONSTITUENT 1, BTU/LBM
C ICONT = 1 MEANS CONTINUOUS SPILL. ICONT=0. FOR NON-CONTINUOUS SPILL
C INST = 1 MEANS INSTANTANEOUS SPILL. INST=0. FOR NON-INSTANTANEOUS SPIL
C LNGIN = NAME OF INPUT FILE
C LNGOUT = NAME OF OUTPUT FILE
C M2 = MULTIPLIER OF PTIM TO OBTAIN PRINT-OUTS AT GREATER TIME INTERVALS
C WHEN 1 IS LARGER THAN N1
C M3 =MULTIPLIER OF PTIM TO OBTAIN PRINT-OUTS AT GREATER TIME INTERVALS
C WHEN 1 IS LARGER THAN N2
C M4 = MULTIPLIER OF PTIN TO OBTAIN PRINT-OUT AT GREATER TIME INTERVALS
C WHEN CALCULATIONS ARE BEING MADE DURING POOL BREAK-UP
C N = TOTAL NUMBER OF INCREMENTS FOR WHICH CALCULATIONS ARE MADE
C N1,N2,N3 = NUMBER OF TIME STEPS AT INCREMENTS OF STEP1,STEP2,STEP3 SEC
C NOSPE = NUMBER OF CONSTITUENTS COMPRISING THE LNG
C NUMBER(1) = NUMBER ASSOCIATED WITH ONE OF THE CONSTITUENTS OF LNG
C PT = TIM
C PT1 = USED IN CALCULATIONS TO SET PRINT-OUT TIME INCREMENT
C PTIM = TIME INTERVAL FOR PRINTOUT OF RESULTS, SEC
C Q(1) = QB(1)*A, FT/SEC
C QB(1) = RATIO OF QBFT(1) TO QBFT(1) TIMES 3.14
C QBFT(1) = HEAT TO VAPORIZE CONSTITUENT 1 ,BTU/LBM
C R = RADIUS OF LNG POOL ON WATER SURFACE
C RBRK = INTERIOR RADIUS OF POOL BREAK-UP
C RDOT = VELOCITY OF POOL SPREAD, FT/SEC
C REGR = REGRESSION RATE OF LNG DURING VAPORIZATION, FT/SEC
C RHO(1) = DENSITY OF CONSTITUENT 1, LBM/CU.FT.
C RHOW = DENSITY OF WATER, LBM/CU.FT
C RMAX = MAX RADIUS LNG POOL ATTAINS
C RSPIL = RATE OF SPILL OF LNG, CU.FT/SEC
C ROAV = AVG DENSITY OF LNG SUPPLIED, LB/CU.FT.
C SPILT = TIME DURATION OF SPILL, SEC
C STEP = ACTUAL TIME STEP USED IN CALCULATION, SEC
C TDELV = TOTAL VOLUME OF LNG VAPORIZED PER TIME STEP, CU.FT.
C TDLV(1) = TOTAL VOLUME VAPORIZED OF CONSTITUENT 1, CU.FT.
C TDLVS = TOTAL VOLUME OF LNG VAPORIZED PER SEC., CU.FT./SEC
C TIM = TIME FROM START OF CALCULATION, SEC
C TNOT = INITIAL TEMPERATURE OF LNG, DEGREES RANKINE
C TVAP(1) = TEMPERATURE AT VAPORIZATION OF CONSTITUENT, DEGREES RANKINE
C TVOL = TOTAL VOLUME VAPORIZED, CU. FT.
C V = VOLUME OF LNG ON WATER SURFACE, CU.FT.
C VA = USED IN CALCULATIONS TO CALCULATE V
C VOL(1) = VOLUME OF CONSTITUENT LEFT ON SPILL SURFACE, CU.FT.
C VOLI = INITIAL VOLUME OF LNG SITTING ON WATER SURFACE TO START CALC'S

```

```

C IN UNITS OF CU. FT.
4 DIMENSION NUMBER(5), FRI(5), RHO(5), HVAP(5), TVAP(5), CP(5), QB(5), Q(5)
1 VOL(5), QBFT(5), DELV(5), FR(5), FRI(5), DLVS(5), TDLV(5)
C READ INPUT DATA
6 READ(2, 1000) INST, ICONT, NOSPE, N1, N2, N3, STEP1, STEP2, STEP3, G, RHO,
1 RSPIL, SPILT, VOL1, TNOT, REGR, HBRK, ROAV, CON, PTIM, M2, M3, M4
C WRITE OUT INPUT DATA
WRITE(3, 1020)
WRITE(3, 1030)
WRITE(3, 1040) INST, ICONT, NOSPE, N1, N2, N3, STEP1, STEP2, STEP3, G, RHO,
1 RSPIL, SPILT, VOL1, TNOT, REGR, HBRK, ROAV, PTIM, M2, M3, M4, CON
WRITE(3, 1050)
7 DO 20 I=1, NOSPE
8 READ(2, 1010) NUMBER(I), FRI(I), RHO(I), HVAP(I), TVAP(I), CP(I)
9 WRITE(3, 1060) NUMBER(I), FRI(I), RHO(I), HVAP(I), TVAP(I), CP(I)
20 CONTINUE
AB=0.0
C INITIALIZE PARAMETERS
22 DO 30 I=1, NOSPE
23 QBFT(I)=(CP(I)*(TVAP(I)-TNOT)+HVAP(I))*RHO(I)
24 VOL(I)=FRI(I)*VOL1
25 AB=AB+(QBFT(I)/QBFT(1))*VOL(I)/VOL1
26 QB(I)=QBFT(I)*3.14/QBFT(1)
TDLV(I) = 0.000
30 CONTINUE
WRITE(3, 1070)
R=(VOL1/3.14)**0.3333
DELRO=RHO-ROAV
V=VOL1
H=R
A=REGR/AB
IF(ICONT.EQ.1) RMAX=(RSPIL/(3.14*REGR))*0.5
STEP=STEP1
N=N1+N2+N3
N2=N2+N1
TVOL = 0.0000
PT1 = 0.0000
TIM = 0.0000
PT=PTIM
IDOT = 0
IF(INST.EQ.1) RMAX=9999.
WRITE(3, 1080) TIM, N, RMAX, R, H, DELRO, A
35 DO 40 I=1, NOSPE
36 Q(I)=QB(I)*A
WRITE(3, 1090) I, VOL(I), QBFT(I), QB(I)
40 CONTINUE
WRITE(3, 1100)
C TRANSIENT CONTINUOUS OR INSTANTANEOUS SPILL CALCULATIONS
DO 350 I=1, N
IF(I.GT.N1) STEP=STEP2
IF(I.GT.N2) STEP=STEP3
TIM=TIM+STEP
IF(TIM.GT.SPILT) RSPIL=0.0
IF(R.EQ.RMAX) GO TO 305
303 RDOT=CON*((G*DELRO /RHO)**0.25)*(V**0.25) / (TIM**.5)
304 R=R+RDOT*STEP
IF(R.GE.RMAX) R=RMAX
IF(R.EQ.RMAX) RDOT = 0.000
IF(R.EQ.RMAX) IDOT = 1
305 TDELV=0.0

```

```

VA=0.0
DENS=0.0
DO 310 J=1,NOSPE
306 DELV(J)=Q(J)*VOL(J)*(R**2)*STEP/V
307 VOL(J)=VOL(J)+RSPIL*FRI(J)*STEP-DELV(J)
308 TDELV=TDELV+DELV(J)
VA=VA+VOL(J)
309 DENS=DENS+RH0(J)*VOL(J)
DLVS(J) = DELV(J)/STEP
310 CONTINUE
TDLVS = TDELV/STEP
TVOL = TVOL + TDELV
V=VA
311 DENS1=DENS/V
DELRO=RH0-DENS1
313 H=V/(3.14*(R**2))
331 DO 340 M=1,NOSPE
332 FRII(M)=VOL(M)/V
333 FR(M)=DELV(M)/TDELV
TDLV(M) = TDLV(M) + DELV(M)
340 CONTINUE
IF(I.GT.N1) PTIM=PT*M2
IF(I.GT.N2) PTIM=PT*M3
PT1=PT1+STEP
IF(IDOT.EQ.1) GO TO 347
IF(H.LE.HBRK) GO TO 347
IF(PT1.GE.PTIM) GO TO 347
GO TO 349
347 CONTINUE
WRITE(3,1110) I,TIM,R,H,DENS1,RD0T
WRITE(3,1115)
WRITE(3,1120) (J,VOL(J),DLVS(J),TDLV(J),FRII(J),FR(J),J=1,NOSPE)
WRITE(3,1130) V,TDLVS,TVOL
IF(IDOT.EQ.1) GO TO 348
PT1 = 0.0000
348 IDOT = 0
349 CONTINUE
IF(H.LE.HBRK) GO TO 600
350 CONTINUE
600 RMAX=R
WRITE(3,1200)
WRITE(3,1210) RMAX,H,TIM
PTIM=PT*M4
K=I
602 DO 650 I=K,N
IF(I.GT.N1) STEP=STEP2
IF(I.GT.N2) STEP=STEP3
TIM=TIM+STEP
604 RBRK=(RMAX**2-(V/(HBRK*3.14)))*0.5
RMK=(RMAX-RBRK)/RMAX
IF(RMK.LT.0.01) GO TO 1660
VA=0.0
TDELV=0.0
606 DO 610 J=1,NOSPE
607 DELV(J)=Q(J)*(VOL(J)/V)*(RMAX**2-RBRK**2)*STEP
VOL(J)=VOL(J)-DELV(J)
IF(VOL(J).LT.0.0) VOL(J)=0.0
VA=VA+VOL(J)
TDELV=TDELV+DELV(J)
DLVS(J) = DELV(J)/STEP

```

```

610 CONTINUE
    TDLVS = TDELV/STEP
    TVOL = TVOL + TDELV
    V=VA
    IF(V.LE.0.0) GO TO 1660
611 DO 620 M=1,NOSPE
612 FR(M)=DELV(M)/TDELV
613 FRII(M)=VOL(M)/V
    TDLV(M) = TDLV(M) + DELV(M)
620 CONTINUE
    PT1=PT1+STEP
    IF(PT1.GE.PTIM) GO TO 630
    GO TO 640
630 CONTINUE
    WRITE(3,1220) I,TIM,RBRK
    WRITE(3,1115)
    WRITE(3,1120) (J,VOL(J),DLVS(J),TDLV(J),FRII(J),FR(J),J=1,NOSPE)
    WRITE(3,1130) V,TDLVS,TVOL
    PT1=0.0
640 CONTINUE
650 CONTINUE
1000 FORMAT(3I2,3I5,5F10.4,/,7F10.4,/,2F10.4,3I5)
1010 FORMAT(12,5F10.4)
1020 FORMAT(1H1,"LNG VAPOR GENERATION FOR A SPILL ON WATER - W. STEIN")
1030 FORMAT(//,2X,"INPUT PARAMETERS")
1040 FORMAT(/,5X,"INST=",12,2X,"ICNT=",12,2X,"NOSPE=",12,2X,"N1=",16,
12X,"N2=",16,2X,"N3=",16,/,5X,"STEP1=",F10.4,2X,"STEP2=",F10.4,2X,
2X,"STEP3=",F10.4,2X,"G=",F10.4,/,5X,"RHOW=",F10.4,2X,"RSPIL=",F10.4,
32X,"SPILT=",F10.4,/,5X,"VOL1=",F10.4,2X,"TNOT=",F10.4,2X,"REGR=",
4F10.4,/,5X,"HBRK=",F10.4,2X,"ROAV=",F10.4,2X,"PTIM=",F10.4,2X,
5X,"M2=",16,/,5X,"M3=",16,2X,"M4=",16,2X,"CON=",F10.4)
1050 FORMAT(//,6X,1H1,3X,6HFRI(1),4X,6HRHO(1),3X,7HHVAP(1),3X,
17HTVAP(1),5X,5HCP(1))
1060 FORMAT(5X,12,5F10.4)
1070 FORMAT(//,2X,"INITIAL AND CALCULATED PARAMETERS AT TIME ZERO")
1080 FORMAT(/,5X,"TIM=",F10.4,2X,"N=",16,2X,"RMAX=",F10.6,2X,"R=",
1F10.6,/,5X,"H=",F10.6,2X,"DELRO=",F10.4,2X,"A=",F10.6)
1090 FORMAT(5X,"I=",12,2X,"VOL(1)",E12.6,2X,"QBFT(1)",E12.6,2X,
1"QB(1)",E12.4)
1100 FORMAT(1H1,2X,"TRANSIENT CALCULATIONAL OUTPUT")
1110 FORMAT(/,6X,"I",4X,"TIME",8X,"R",9X,"H",6X,"DENSITY",4X,"RDOT",/,
116,5F10.6)
1115 FORMAT(15X,"VOL(1)",9X,"DLVS(1)",8X,"TDLV(1)",3X,"FRII(1)",4X,
1"FR(1)")
1120 FORMAT(2X,16,3E15.6,2F10.6)
1130 FORMAT(/,1X,"TOTALS",1X,3E15.6)
1200 FORMAT(1H1,2X,"POOL BREAKUP CALCULATIONAL OUTPUT")
1210 FORMAT(/,2X,"RMAX=",F10.6,2X,"HBRK=",F10.4,2X,"TIM=",F10.6)
1220 FORMAT(/,2X,"I=",16,2X,"TIME=",F10.4,2X,"RBRK=",F10.6)
1660 WRITE(3,2000)
2000 FORMAT(5X,"LNG HAS EVAPORATED - PROBLEM FINISHED")
2010 FORMAT(5X,"MAX RADIUS ATTAINED AT TIME =",F10.6)
    CALL EXIT
    END

```